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Quantifying the risks of radiation exposure

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Summary

The considerations leading to the recommendation of dose-equivalent limits by the International Commission for Radiological Protection are outlined. The dose-equivalent limits are based on radiation risk factors estimated from effects of radiation observed over many decades. These limits are designed to ensure that radiation exposure does not entail a greater risk than that experienced in other safe occupations or accepted by the general public in everyday life. The risk factors should, however, not be used to assess the risk to patients from diagnostic procedures.

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The commissioning of the Koeberg nuclear power station during 1984 has created in the public an awareness of and interest in the risks due to radiation exposure. Concern has been expressed about the level of knowledge possessed by medical practitioners of the risks due to radiation exposure.[1]

Recently the Atomic Energy Corporation (AEC) of South Africa issued document NKKS 10/82[2] in which revised dose-equivalent* limits for radiation workers were laid down. These latest dose-equivalent limits were based on the recommendations of the International Commission for Radiological Protection (ICRP).[3,4]

It is thus appropriate to review briefly the present state of knowledge of risks from radiation, as compiled by the ICRP, and to outline the considerations leading to the laying down of dose-equivalent limits for radiation workers and the general public.

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*For radiation protection purposes, the radiation received by tissue is quantified in terms of the dose equivalent, its SI unit is the sievert (Sv). 1 Sv = 100 rem.

International Commission for Radiological Protection (ICRP)

The ICRP was established in 1928 as the International X-ray and Radium Protection Commission by the Second International Congress of Radiology held in Stockholm, Sweden. It assumed its present name in 1950, and functions under the auspices of the International Congress of Radiology. The Commission consists of a Chairman and not more than 12 members. The selection of members is made by the ICRP from nominations submitted to it by the national delegations to the International Congress of Radiology and by the ICRP itself. The selections are subject to approval by the International Executive Committee of the Congress. Members of the ICRP are chosen on the basis of their recognized activity in the fields of medical radiology, radiation protection, physics, health physics, biology, genetics, biochemistry and biophysics with regard to an appropriate balance of expertise rather than to nationality. Not less than 3 but not more than 5 members are changed at any one Congress.

The ICRP may invite individuals to give special technical advice, and may also establish such committees as it deems necessary to perform its functions. Much of the work is performed by *ad hoc* task groups, by means of which the Commission has been able to call on the services of a large number of individuals who are not members of a committee.

The Commission has regularly published reports and recommendations. These are now available in the form of a review

journal, *Annals of the ICRP*, published by Pergamon Press, Oxford.

Recommendations of the ICRP (publication No. 26)

The ICRP bases its recommendations on the radiation effects (or absence of effects) observed over several decades. These include, for example, reported data obtained from experiments on animals and lower organisms, observations on humans irradiated for therapeutic purposes, Japanese survivors of nuclear explosions, miners in radioactive mines and radiation workers.

It distinguishes between stochastic and non-stochastic effects. Stochastic effects are effects for which the probability of an effect occuring rather than its severity is regarded as depending on the radiation dose. It is assumed that no 'safe' threshold dose exists below which no such effects would occur. The most important stochastic effects are carcinogenesis and hereditary effects. (It should be pointed out that a latent period which may vary from a few to 30 years or more may elapse between the exposure to radiation and the occurrence of cancer.[5] The length of the latent period depends on the dose, type of cancer and age of the individual.) Non-stochastic effects are those for which the severity of the effect varies with dose, and for which a theshold may occur. Examples of non-stochastic effects are induction of cataract of the lens of the eye, non-malignant damage to skin, and cell depletion in the bone marrow leading to haematological deficiencies.

One basic assumption of the ICRP is that there is a linear relationship without threshold between dose and probability of a stochastic effect, within the range of exposure encountered in radiation work.

From the aforesaid data the ICRP has estimated the probability of inducing fatal malignant disease, non-stochastic diseases or substantial genetic defects in liveborn descendants. This probability expressed per unit dose is termed the 'risk factor'. The risk factor is the proportionality constant of the relationship between dose and probability of an effect occurring. Risk factors for those tissues from which the majority of all induced malignancies appear likely to arise are listed in Table I.

These risk factors are very similar to those reported in a separate analysis by the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) in 1977.[5] Concerning the combined risk of malignant disease in all remaining unspecified tissues of 5×10^{-3} Sv^{-1} it is assumed that no single tissue is responsible for more than one-fifth of this value. It is recognized that the risk factors vary with age and sex, but the variations with age and sex in total risk from an individual exposure are not considerable. The weighting factors listed in document NKKS 10/82[2] are simply the ratios between the risk factors of the various organs and the total stochastic risk factor, $16,5 \times 10^{-3}$ Sv^{-1}, obtained by summing all the risk factors (omitting the additional hereditary damage to later generations).

TABLE I. RISK FACTORS FOR RADIATION-INDUCED STOCHASTIC EFFECTS[3]

Effect	Risk factor Sv^{-1}	Risk factor rem^{-1}
Breast cancer	$2,5 \times 10^{-3}$	$2,5 \times 10^{-5}$
Leukaemia	$2,0 \times 10^{-3}$	$2,0 \times 10^{-5}$
Lung cancer	$2,0 \times 10^{-3}$	$2,0 \times 10^{-5}$
Bone cancer	$5,0 \times 10^{-4}$	$5,0 \times 10^{-6}$
Thyroid cancer mortality	$5,0 \times 10^{-4}$	$5,0 \times 10^{-6}$
Combined risk of malignancy in other unspecified tissues	$5,0 \times 10^{-3}$	$5,0 \times 10^{-5}$
Serious hereditary ill-health within first two generations (irradiation of either parent)	$4,0 \times 10^{-3}$	$4,0 \times 10^{-5}$
Additional hereditary damage to later generations	$4,0 \times 10^{-3}$	$4,0 \times 10^{-5}$

For purposes of radiation protection of individuals, the mortality risk factor for radiation-induced cancers is taken to be about $10^{-2}Sv^{-1}$ (10^{-4} rem^{-1}) as an average for both sexes and all ages.

Regarding non-stochastic effects, it was concluded that a total dose equivalent of 15 Sv would be below the threshold for the production of any lens opacification that would interfere with vision. (Later information indicated that this value was somewhat high, and the recommended annual limits were subsequently reduced.[4]) Skin is thought to be much less liable to develop fatal cancer after irradiation than the tissues already discussed. Limitation of the dose to the skin to below 20 Sv over a lifetime should prevent cosmetically unacceptable changes. Induction of permanent sterility would require several Sv in both sexes. It is well known that exposure before birth or during childhood may interfere with subsequent growth and development. Susceptibility to induction of certain malignancies is also higher than during adult life.

In the light of evidence from heavily irradiated populations observed for periods up to 30 years, the ICRP concluded that it is unlikely that any major hazard from radiation has been overlooked.

Recommended limits of radiation dose

Occupational exposure

The aim of radiation protection should be to prevent non-stochastic effects and to limit the probability of stochastic effects to levels deemed acceptable. The ICRP recommends upper limits of exposure but recommends that no exposure be unjustified in relation to its benefits and that any necessary exposures are kept as low as reasonably achievable (the ALARA principle).

Non-stochastic effects may be prevented by setting annual dose-equivalent limits at sufficiently low values so that no threshold dose would be reached, even following exposure for the whole lifetime or total period of working life. These limits are 0,5 Sv (50 rem) for all tissues except the lens of the eye for which a limit of 0,15 Sv (15 rem) is recommended.

Regarding stochastic effects resulting from occupational radiation exposure, the Commission recommends upper limits of radiation dose which will ensure that the calculated rate of fatal malignancies induced by the radiation will be comparable to the occupational fatality rate of industries recognized as having high standards of safety. These are considered to be those in which the annual mortality due to occupational hazards does not exceed 10^{-4} deaths per person. Levels of risk experienced in South African industry are listed in Table II.[6]

It must be realized that the mortality figures for safe occupations give the average risk for a worker, and that some workers will be exposed to much higher risks. A similar situation applies in radiation work. Experience has shown that in circumstances where the ICRP's recommendation of an annual dose-equivalent limit of 50 mSv (5 rem) has been applied in large occupational groups, the arithmetic mean was about 5 mSv (500 mrem) with very few values approaching the limit. Multiplying the risk factor of 10^{-2} Sv^{-1} by this mean dose yields an average risk factor for radiation work which is

TABLE II. AVERAGE ANNUAL INDUSTRIAL FATALITY RATES[6]*

Industrial class	Deaths/person/yr
Agriculture and forestry	**$3{,}28 \times 10^{-4}$**
Fishing	**$2{,}33 \times 10^{-3}$**
Mining	**$8{,}35 \times 10^{-4}$**
Building and construction	**$7{,}68 \times 10^{-4}$**
Food, drink, tobacco	**$2{,}27 \times 10^{-4}$**
Chemical	**$2{,}49 \times 10^{-4}$**
Trade, commerce	**$1{,}73 \times 10^{-4}$**
Banking, finance, insurance	**$6{,}78 \times 10^{-5}$**
Transport	**$1{,}00 \times 10^{-3}$**
Medical services	**$4{,}25 \times 10^{-5}$**
Professional services	**$4{,}75 \times 10^{-5}$**

*Six-year mean 1965 - 1970.

TABLE IV. ANNUAL AVERAGE FATALITY RATES FOR GENERAL PUBLIC[6]

Cause	Deaths/person/yr
Motor vehicles	**3×10^{-4}**
Drowning	**6×10^{-5}**
Railways	**1×10^{-5}**
Lightning	**2×10^{-6}**
Venomous insects	**2×10^{-6}**

comparable to the average risk in other safe industries. Although the ICRP's dose-equivalent limits are intended to ensure adequate protection even for the most highly exposed individuals a higher than average risk applies to an individual consistently exposed to levels near the limit. Since the actual risk decreases linearly with dose, the ALARA principle should be applied at all times. Table III gives a summary of the dose-equivalent limits laid down by the South African AEC in document NKKS 10/82, which are based on the recommendations of ICRP publication No. 26.

Individual members of the public

The general public is subject to a variety of hazards, for example, public and private transport that contribute to the total risk to which they are exposed. The acceptance of this risk is motivated by certain benefits that may not otherwise be received, by an assessment of the social cost of reducing the risk, or by regarding the risk as negligible. Table IV lists some annual average fatality rates for the general public in South Africa.[6]

The ICRP concluded that the level of acceptability for fatal risks to the general public is an order of magnitude lower than for occupational risks. Accordingly they recommend a whole-body dose-equivalent limit of 5 mSv (0,5 rem) per year for members of the public. An overriding dose-equivalent limit of 50 mSv to prevent non-stochastic effects should be applied. This is considerably lower than that recommended for occupational exposure in order to ensure that the possible longer exposure period and the practical difficulties in controlling the total exposure from all sources will not result in threshold doses for non-stochastic effects being reached.

In document NKKS 10/82 the AEC quotes as an example that 0,25 mSv (25 mrem) has been laid down as the annual upper limit of dose equivalent that an individual member of the public may receive as result of normal releases of radionuclides by the Koeberg nuclear power station.[2] This figure was arrived at by adopting in effect a figure of 5×10^{-6} deaths per person per year as the maximum acceptable fatality rate and a radiation risk factor of 2×10^{-2} deaths per Sv (2×10^{-4} rem^{-1}). It is estimated that the average risk in a group in which this maximum may occur would be 50 times lower.[6]

Patient exposures

When exposed to radiation during a medical examination, the patient receives benefit from the procedure. Accordingly, it is not appropriate to apply the dose-equivalent limits for exposure of radiation workers or the general public to patient exposures. With certain medical exposures a very much higher level of risk may be justified than that deemed appropriate for radiation workers or the general public. As a general principle, the ICRP recommends that unnecessary exposures should be avoided, necessary exposures should be justifiable in terms of benefits that would not otherwise have been received, and that the doses actually administered should be limited to the minimum amount consistent with the medical benefit to the individual patient. Nevertheless it is important that the danger of radiation exposure should not be overestimated since this might lead to the rejection of justified examinations.

The aim of radiation protection of the patient has gradually shifted from a concern about population exposures and hereditary effects to the ambition of limiting the risk to the individual patient.[7] However, caution has been expressed against a tendency to use the risk factors for predicting the actual numbers of cases in any particular situation.[8] The risk factors should rather be regarded as upper estimates of risk, based on experience mainly with external radiation at high doses and dose rates and often with high linear energy transfer.[9] Extrapolation to irradiation conditions used in clinical practice might be too inaccurate to use them as criteria for comparing the risk from different clinical procedures.

Factors such as differences in linear energy transfer, dose and dose rate could cause the risk of certain diagnostic radiation procedures to be lower.[5] The length of the latent period should also be considered in relation to the age of the patient.

Nevertheless the ICRP has used the risk factors to obtain an 'approximate estimation of the magnitude' of the risk of fatality for x-ray chest examination of adult females (Table V).[7] This calculation illustrates a different approach from that based on the critical tissue concept which the ICRP followed

TABLE III. DOSE-EQUIVALENT LIMITS AND DERIVED DOSE RATES FOR RADIATION WORKERS[2]

Tissue	Annual limit (mSv)	Weekly average (mSv)	Hourly average (mSv)
Whole body	**50 (5 rem)**	**1 (100 mrem)**	**0,025 (2,5 mrem)**
Skin, extremities	**500 (50 rem)**	**10 (1 000 mrem)**	**0,25 (25 mrem)**
Lens of eye	**150 (15 rem)**	**3 (300 mrem)**	**0,075 (7,5 mrem)**

TABLE V. ESTIMATION OF RADIATION RISK TO ADULT FEMALES FOLLOWING TYPICAL TISSUE DOSES* FROM AN X-RAY CHEST EXAMINATION[7]

Organ, tissue	Estimated mean absorbed dose (mSv)	Risk factor (10^{-4} Sv^{-1})	Radiation risk (deaths per person x 10^{-6})
Lung	**0,20**	**20**	**0,40**
Breast	**0,14**	**2 x 25**	**0,70**
Bone marrow	**0,03**	**20**	**0,06**
Thyroid	**0,07**	**5**	**0,04**

*Doses to other organs are negligible.

before 1977 and which is still followed by the United States National Council on Radiation Protection and Measurements. According to the critical tissues concept the dose equivalent to an individual should be limited by that dose to an organ which would result in the greatest detriment to the individual or his/her progeny.[10] In the new ICRP approach the dose equivalent should be limited by the total stochastic risk (if non-stochastic effects may be excluded) obtained by summation of the risks to all organs.[7]

Since the risk factors were largely obtained from external irradiation of humans they might be especially inappropriate for assessing risks from internal emitters[10] as used in nuclear-medicine procedures. Apart from the factors mentioned above, the risks from internal emitters might be different due to non-homogeneous distribution of activity at the cellular level coupled with low-energy electron emission (e.g. iodine-125[11]). Certain observations lend support to the concept of microdosimetry, namely that the biological effectiveness of radiation depends on the pattern of energy deposition within microscopic volumes having diameters of 1 nm - 1 μm.[12] It is known for example that ^{131}I is about 10 - 20 times less effective on a rem-for-rem basis than x-ray therapy for ablating the thyroid.

Johnson and Myers[11] showed that theory suggests that differences in linear energy transfer and dose rate might cause ^{131}I to be 2 - 10 times less effective than x-rays at high dose rate for induction of thyroid cancer in humans. They reviewed data based on animal experiments and experience in humans, but could not, however, find convincing evidence that there is a great difference in the efficiency of ^{131}I and x-rays for induction of thyroid cancer. Animal experiments suggested that low doses of ^{131}I should be as efficient or at most three times less efficient than x-rays for inducing thyroid cancer. They quoted a large follow-up study conducted by Holm *et al.* on patients who had received ^{131}I for diagnosis. No significant increase in thyroid cancer had been found. A significant increase would have been expected if a risk estimate of 100 x 10^{-4} Sv^{-1} was used, but not if a value of 14 x 10^{-4} Sv^{-1} was used.

In summary then, the risk estimates of the ICRP are conservative.[10] They thus provide a sound basis for radiation protection in order to ensure that individuals are not exposed to harmful amounts of radiation. They should, however, not be used at present to predict actual numbers of deaths from radiation from clinical diagnostic procedures.[7] Decisions based on overestimation of radiation risks could be to the detriment of a patient if it should exclude him/her from the benefits of a particular procedure.

The ALARA principle

It must be emphasized that dose-equivalent limits recommended by regulating authorities are not intended to be considered 'safe' doses, but are regarded as maximum permissible levels. An overriding principle in recommendations is that all radiation doses are to be kept as low as reasonably achievable (the ALARA principle). Careful thought may be required to establish what is *reasonably* achievable. For a general discussion of relevant cost-benefit analysis the reader is referred to ICRP publication No. 26.[3] However, it must be pointed out that in weighing the 'cost' of radiation exposure, the hazards of alternative procedures must be considered. It would be wrong to restrict radiation exposure to such a level that an alternative more hazardous procedure has to be adopted.

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